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Low Cycle Fatigue Behavior
Of Joined Structures

RESIDUAL STRESS REDISTRIBUTION IN WELDED BEAMS SUBJECTED TO CYCLIC BENDING (PART 1)

by
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Fritz Engineering Laboratory Report No. 358.5

Low Cycle Fatigue

RESIDUAL STRESS REDISTRIBUTION IN WELDED BEAMS SUBJECTED TO CYCLIC BENDING
(PART I)

by

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This work was conducted as part of a study of low-cycle fatigue, sponsored by the Office of Naval Research, Department of Defense, under contract N 00014-68-A-514; NR 064-509.

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TABLE OF CONTENTS

ABSTRACT

The purpose of this investigation is to compare the residual stresses in an as-fabricated beam with those in similar beams after a number of bending cycles.

The study is a part of a major research program designed to provide information on the behavior and design of joined structures subjected to low cycle fatigue.

Four beams fabricated from flame-cut plates were evaluated, and three different steel grades ASTM A514, A441 and A36, were considered.

This study includes measurements of the residual stresses present in all four beams; the method of sectioning was used to determine their magnitude and distribution. The measured stress redistribution after loading is compared with theoretical predictions.

It was not possible to obtain enough information on the redistribution of residual stresses because, for all beams, only measurements either before or after loading were

available. Thus, it was not possible to decide if the differences in residual stress patterns in similar beams were due to loading or due to fabrication. Also, the applied load was very small and almost no plastification was accomplished. In the second phase of this study, tests will be performed in such a way that will allow measurements before, during and after the bending moment has been applied, and the magnitude of bending moment will be high enough to plastify part of the section.

1. INTRODUCTION

This report presents the results of a comparison between the residual stresses in an as-fabricated beam and the residual stresses in beams subjected to high cycle alternating load. The magnitude of the residual stress redistribution due to bending is investigated.

Residual stresses are the stresses remaining after the fabrication of a steel structure or structural member.[1,2,3] They result from plastic deformations caused by thermal differentials during cooling, by mechanical treatment, or both. They normally occur after rolling, flame-cutting, welding, or straightening of the member or structure. The magnitude of tensile residual stresses is often close to the yield point of the parent material in the welded zones.

Residual stresses may be a very significant factor in the fatigue life of structural members. The magnitude and distribution of residual stresses is known to effect the fatigue,[4] stress corrosion,[4] brittle fracture,[5] and buckling behavior of members.[6] Residual stresses have been measured in very many structural shapes, as part of studies on column strength.

Information about residual stresses in as-fabricated beams as well as in beams subjected to bending is needed to evaluate behavior in the low-cycle fatigue range, and crack initiation and growth.

Four different beams were evaluated in this investigation. The as-fabricated beam, marked PWC-001, was fabricated from A514 steel. Three beams already tested in high-cycle fatigue were also examined. The beam marked PWC-131 was fabricated from A514 steel, the beam PWA-131 from A36 steel, and the beam marked PWB-311 from A441 steel.

The purpose of this investigation was to obtain information about the distribution of residual stresses in beams subjected to repeated bending prior to further investigation of crack initiation and propagation. Of interest was the residual stress prior to loading and the subsequent redistribution, if any, due to the repeated application of the load.

2. MATERIAL PROPERTIES AND SPECIMEN GEOMETRY

The yield strength, tensile strength and ductility are summarized in Table 1.

The dimensions of all four beams are indicated in Fig. 1 and Table 2. Beams PWC-131 and PWA-131 were subjected to alternating loading[7] that varied from -19.4 kips to 42.9 kips. Beam PWB-311 was loaded between 29.8 and 63 kips. The loading scheme is shown in Fig. 1 and the corresponding stresses are listed in Table 3.

The beams were fabricated by the automatic submerged arc process, with a fillet weld of 3/16" inch placed on each side of the web. Lincoln L60 electrodes were used for A36 and A441 steels and L61 electrodes for the A514 steel. All beams were assembled in a jig and tack welds were used to maintain the alignment prior to placing the web to flange connection. The sectioning of the specimens is shown in Figure 2.

3. RESIDUAL STRESS MEASUREMENTS

The specimens for the residual stress measurements were taken from beam regions without visible defects or cracks. Beams PWA-131 and PWB-311 were examined only in the shear spans. The A514 steel beam PWC-131 was examined at two locations, one in the shear span and the other at the center line in the constant moment region.

The A514 as-fabricated beam (PWC-001) was selected at random from the series and was not subjected to a prior load history.

The method of sectioning[8] was used for the residual stress measurements. Gage holes were drilled in all surfaces of the beams and the gage length was taken as 10 inches. The measurements were taken with a mechanical gage and were recorded before and after sectioning. Young's modulus was assumed to be 30,000 ksi.

4. RESULTS

The residual stress distribution for the as-fabricated beam (PWC-001, A514) is shown in Fig. 3. Coupon tension tests (Table 1) of the A514 steel plate had indicated that static yield strength was 111.1 ksi. The tension residual stresses at the flange tips developed mainly from flame-cutting, and modified by welding of the plate, were about 60 ksi. In the vicinity of the flange to web fillet welded connection, the tension residual stresses were observed to approach the yield strength. As expected, the same large tension residual stresses were observed in the web adjacent to the fillet welds. Nearly uniform compressive stress regions were observed in both the flanges and web. The stresses were substantially smaller and existed over large regions in order to maintain internal equilibrium. The average residual compression stress in the flanges was about 18 ksi and its magnitude was about 13 ksi in the web.

Figures 4 and 5 show the residual stress distribution for A514 steel beam PWC-131 at mid-span and in the shear span section. On the surfaces adjacent to the welded zone at the flange tips, the residual tensile stresses are close to the magnitude observed in the as-fabricated beam. It is apparent from the comparison of Figs. 4 and 5, that some redistribution of the residual stress due to different applied bending moment occurred in the section.

Figure 6 summarizes the results obtained for the A36 steel beam PWA-131. The static yield stress was 35.4 ksi for the A36 steel plate (Table 1). The maximum tensile residual stress measured in the base metal was about 30 ksi. (The weldment yield point was higher than the base metal so that this comparatively large tensile stress could exist.) At the flange tips the residual tensile stress was in the range of 10 to 20 ksi. The compressive residual stress in the flanges was about 13 ksi and 17 ksi in the web. In beam PWA-131 (A36), there was observed a larger zone in tension adjacent to the weldment than in the other beams, see Figs. 3, 4, 5 and 6.

Figure 7 shows the pattern of residual stresses in the A441 steel beam PWB-311. The static yield stress of the base metal was 59.2 ksi (Table 1). The residual tensile stress in the welded zone was nearly equal to 70 ksi. The range of variation for the parent material in the tension zone of the flanges was between 40 and 57 ksi. In the web the average compression was 17 ksi. The flange tips were subjected to tension residual stresses of about 50 ksi.

After the determination of residual stresses by sectioning, force and moment equilibrium was checked with

$$P = \int_{area} \sigma_r \cdot da \quad \text{and} \quad M = \int_{area} \sigma_r \cdot y \cdot da$$

where

P = Normal Stress (kips)

M = Moment

σ_r = Residual Stress

y = Distance From Neutral Axis

da = Differential Element of Area

An unbalanced tension force of 0.66 kips was found in the middle section of beam PWC-131, corresponding to a stress of 0.072 ksi. The unbalanced force in the shear span was +6.5 kips (0.71 ksi). The as-fabricated beam (PWC-001, A514) showed an unbalanced compressive stress of 1.5 ksi. In all three cases, the unbalanced stress was considered negligible.

5. ANALYSIS AND DISCUSSION

A theoretical study was undertaken to predict redistribution of the residual stress from the initial as-fabricated condition to the loaded condition. It was assumed that the residual stresses were completely redistributed after the first cycle of the loading was applied. The gradual residual stress redistribution due to cycling was not investigated.

Three cyclically tested beams of three different steel grades, A36, A441, and A514, and one as-fabricated beam A514 steel were used in the investigation.

5.1 Assumption for the Stress Redistribution

This analysis of residual stress redistribution due to cyclic loading assumed that the redistribution occurred completely during the first loading cycle. This assumption will be examined in future tests to see how the plastification of the beam develops. Special instrumentation will be required in order to record the strain history during the cycling loading. The plastification of beams investigated in this study was negligible.

Residual stress redistribution obtained both from the theoretical analysis and the test, is very sensitive to the assumed initial residual stress.

5.2 Residual Stress Patterns

Figures 8, 9, 10, 11 and 12 summarize the measured residual stress patterns for all the beams for the inner and outer surfaces of both flanges as well as for the web. As expected, the higher the steel grade, the higher the residual tensile stress in the welded zone. (See also Figs. 3 through 7).

5.3 Theoretical Analysis and Comparison

A computer program was developed to predict residual stress redistribution. The cross-sectional area of each beam was divided in 212 elements (52 in the web and 80 in each flange). The stress-strain curves obtained from coupon tests were idealized by using two straight lines ($\sigma = E \cdot \epsilon$ and $\sigma = Fy$). The measured residual stresses were averaged with respect to the axes of symmetry (axis x and y). It was assumed that plane cross section remains plane during loading and unloading. The change in elastic-plastic stress distribution was computed after the bending moment was applied (Fig. 13 a). Equivalent fictitious elastic stresses corresponding to the applied bending moment were evaluated (Fig. 13 b). The change in residual stress was found by determining the difference between the elastic-plastic distribution given in (Fig. 13 a) and the equivalent stresses shown in (Fig. 13 b). The results are shown in (Fig. 13 c). The neutral axis was assumed at the mid-height prior to loading. When bending moment was applied, the neutral axis was assumed to remain in its original position unless the bending exceeded the elastic limit. When plastic deformation took place in an element, the analysis assumed that the area of the element was zero for further increment of moment. Thus, the stress distribution that resulted changed the position of the neutral axis.

Figures 14 and 15 compare the residual stresses measured in A514 steel beams, PWC-001 (as-fabricated) and PWC-131 (mid-span). The residual stresses shown for beam PWC-131 were obtained after the beam was subjected to repeated bending. When the maximum bending moment used during the test was applied, the theoretical analysis indicated that the as-fabricated beam (PWC-001) was not affected. The applied moment was not big enough to start plastification in the section. Therefore, no redistribution was obtained. It appears probable that the residual stresses shown in both figures are the initial residual stresses. If the applied bending moment did not change the residual stress pattern, the difference in residual stresses in the as-fabricated beam and beam PWC-131 is probably due to variations in the fabrication.

Figures 16 and 17 show the residual stress patterns measured in the mid-span and shear span of A514 steel beam PWC-131. There is little difference in the residual stress distributions given in Figs. 16 and 17.

The theoretical analysis also indicated that the number of plastified elements was negligible and that no redistribution of residual stresses was obtained. In order to verify the theoretical analysis, a further investigation is proposed using the remaining portion of the A514 steel beam (as-fabricated, PWC-001). The strains will be recorded before, during and after loading in the middle section. The computer program will be used to compute the yielded portion of the cross section after bending moment is applied. The theoretical analysis considers 212 cross sectional elements. The computer program is not sensitive enough when only a few elements yield, which is a disadvantage if crack initiation is investigated. An increased number of elements may be required and the different material properties of parent and weld material should be considered.

The flow chart of the computer program is given as Fig. 18.

6. CONCLUSIONS

The investigation described in the study is concerned with the residual stress redistribution in welded beams after cyclic bending. Using the method of sectioning, residual stresses were measured in four specimens that had been subjected to prior alternating loading and in one as-fabricated specimen.

A theoretical analysis and a computer program were developed to permit the calculation of the residual stress redistribution in beams subjected to bending. Redistribution was assumed to occur completely during the first loading cycle. The residual stress distribution from the theoretical analysis was compared with the measured stress patterns in a loaded beam. The results were discussed, and the main conclusions are as follows:

1. Redistribution of residual stresses in a beam will take place if the loading exceeds the elastic carrying capacity of the beam. The redistribution is very difficult to detect and measure if just a very small part of the section yields.

2. The results of residual stress measurements in welded beams at the shear and mid-spans section in the A514 steel grade(PWC-131), are similar assuming that the initial stress pattern and mechanical properties do not vary along the beam. The redistribution obtained by measurement was compared with theoretical analysis, but no satisfactory results were obtained. The applied bending moment was too low, and therefore, almost no plastification was accomplished. In the second phase of this investigation, the applied bending moment, will be increased.

3. The specimens and the initial data were not sufficient information to evaluate the gradual residual stress redistribution during cycling. To allow recording and investigation of hysteresis characteristics of residual stress patterns in a beam, a new test is suggested.

4. The residual stress redistribution obtained from the comparison of the as-fabricated beam and the loaded beam is not very reliable

because of the possible difference in initial residual stress pattern in both beams due to fabrication and handling. To obtain accurate data on redistribution, another test is suggested using the remainder of the as-fabricated A514 steel beam. The strains should be recorded before the loading is applied, under the load and after unloading. Material properties of flange, weldment and web will be tested and introduced in the theoretical evaluation. Eventually, the residual stress pattern will be measured using the method of sectioning and residual stress will be evaluated for all three stages.

5. The analysis of residual stress redistribution described is not applicable for cracked beams, where the assumption that plane section remains plane is no longer true after the loading is applied.

7. ACKNOWLEDGEMENTS

This paper has been carried out as a part of the Project 358, "Low Cycle Fatigue Behavior of Joined Structures", in order to provide information about the redistribution of residual stresses in their welded slopes subjected to cyclic bending.

The investigation was conducted at Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania. The Office of Naval Research, Department of Defense, sponsored the research under Contract N 00014-68-A-514; NR 064-509.

The program manager for the overall research project is Lambert Tall to whom thanks are due for his advice during the study and his assistance in the preparation of this report.

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Dr. Lynn S. Beedle is Director of Fritz Engineering Laboratory, and Joseph F. Libsch is Vice-President for research, Lehigh University.

8. TABLES

STEEL GRADE	STATIC YIELD STRENGTH (ksi)		TENSILE STRENGTH (ksi)		% ELONG IN 8 IN.	
	MEAN	STD.DEV.	MEAN	STD. DEV.	MEAN	STD.DEV.
A36 (WELDED)	35.4	0.68	61.10	1.15	30.75	0.72
A441 (WELDED)	59.2	3.72	85.45	4.07	21.50	3.15
A514 (WELDED)	111.06	2.30	116.9	2.40	12.70	0.83

Table 1 MECHANICAL PROPERTIES

SHAPE DESIGNATION	TOP FLANGE THICKNESS IN.	TOP FLANGE WIDTH IN.	WEB THICKNESS	BOTTOM FLANGE THICKNESS IN.	BOTTOM FLANGE THICKNESS IN.	DEPTH IN.	STEEL GRADE
PWC-001	0.384	6.78	0.297	0.384	6.79	13.87	A514
PWC-131	0.384	6.78	0.297	0.384	6.80	13.87	A514
PWA-131	0.374	6.62	0.277	0.372	6.65	13.77	A36
PWB-311	0.374	6.58	0.284	0.374	6.62	13.80	A441

Table 2 SECTION DIMENSIONS

SHAPE DESIGNATION	CYCLES/ MIN.	MAX LOAD (KIPS)	MIN LOAD (KIPS)	MAX STRESS (KSI)	MIN STRESS (KSI)	CYCLES TO FAILURE
PWC-001						
PWC-131	250	42.9	- 20.1	20	- 10	783000
PWA-131	250	40.2	- 19.4	20	- 10	676900
PWB-311	500	63.0	29.8	32	14	3080100

Table 3 <u>HISTORY OF LOADING</u>

9. FIGURES

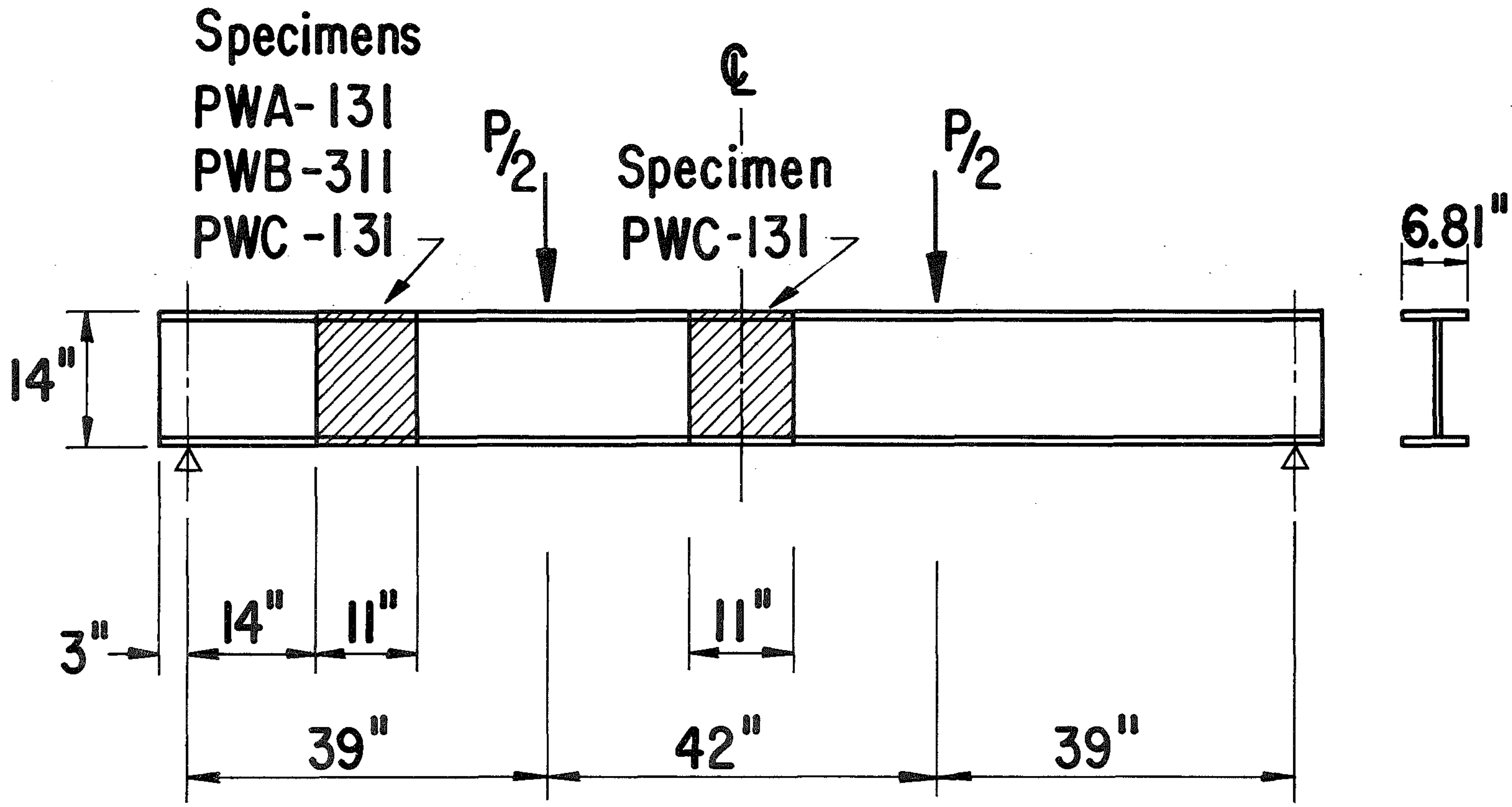

Fig. 1 Test Specimens

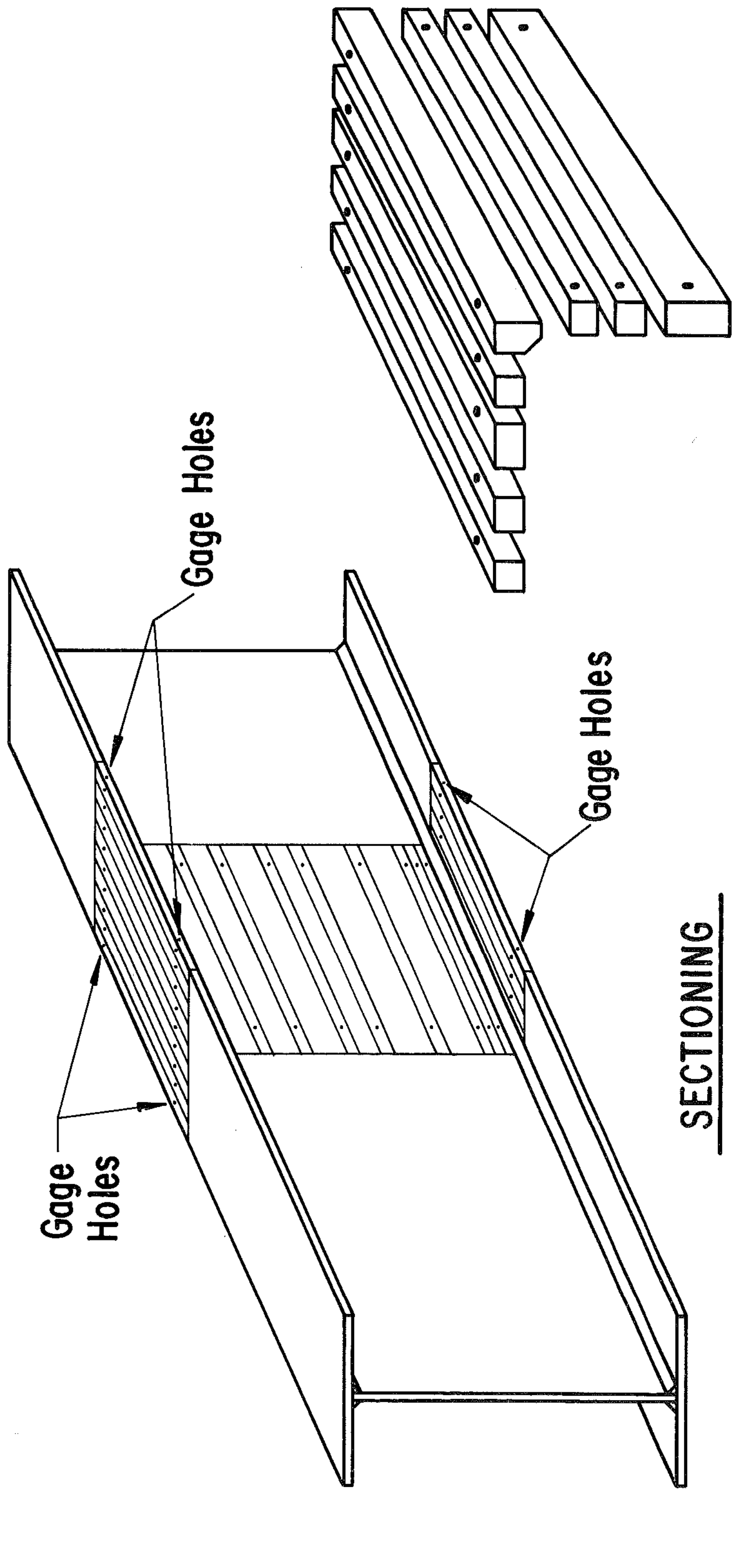

Fig. 2 Sectioning of the Specimens

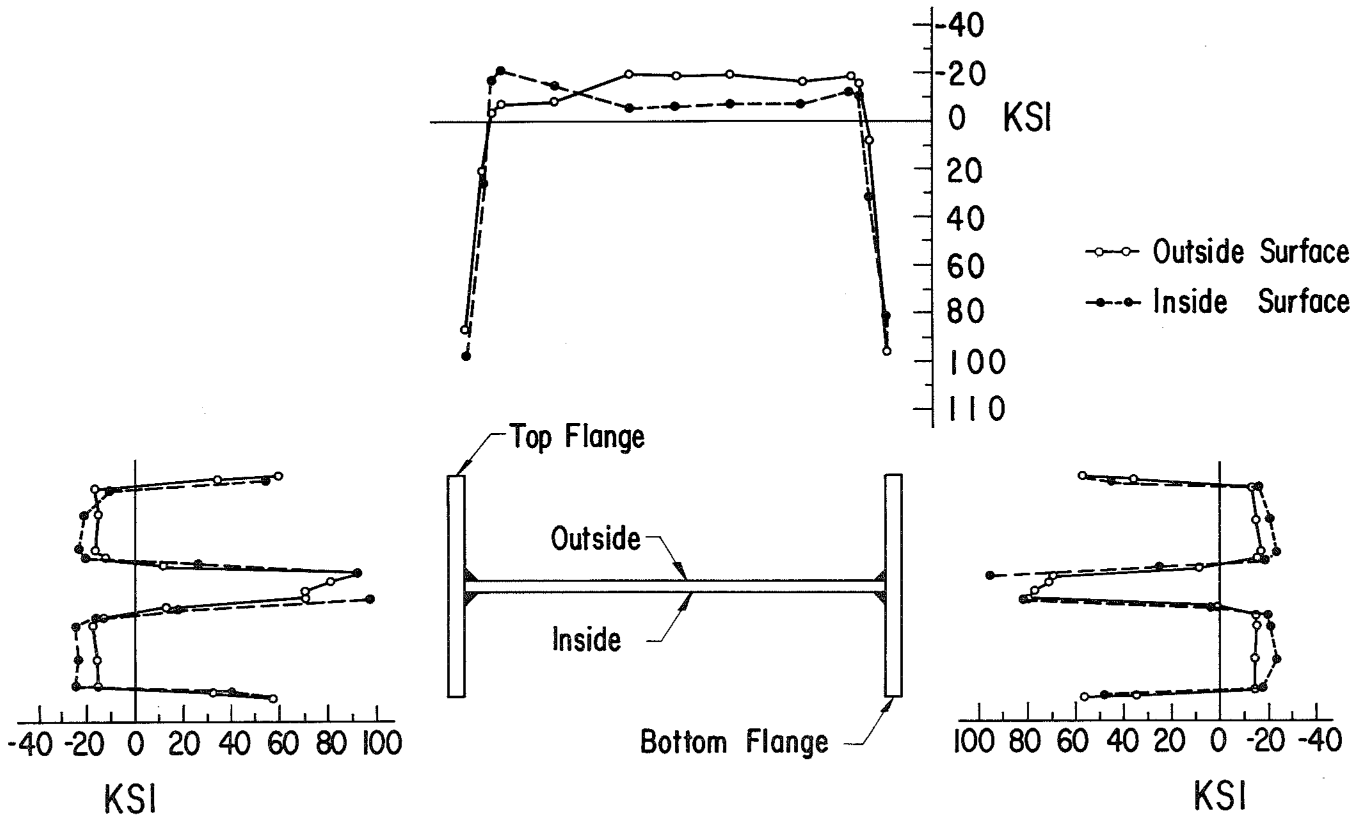

Fig. 3 Residual Stresses in a Welded Shape PWC-001 (as-fabricated) Flame Cut Plates, A514 Steel.

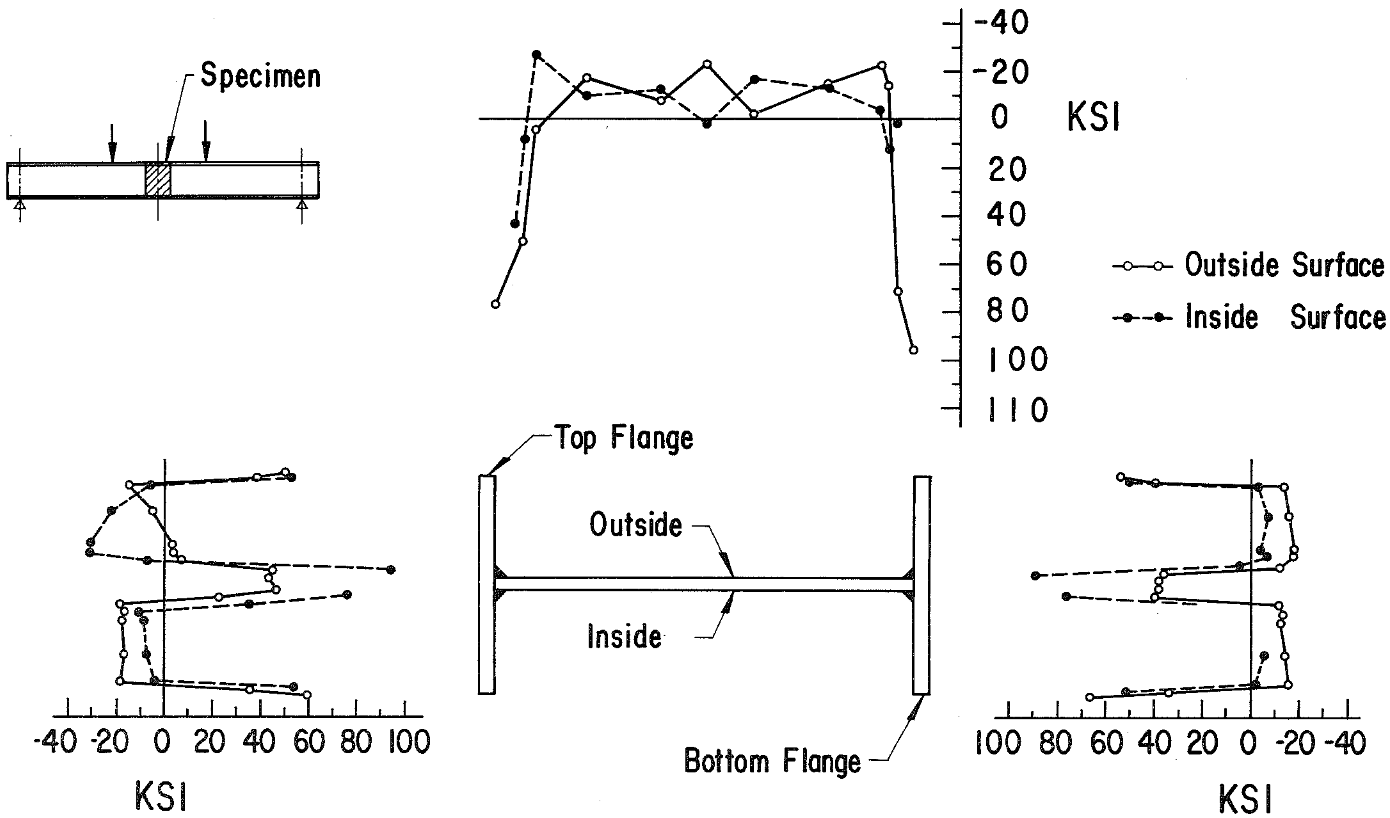

Fig. 4 Residual Stresses in a Welded Shape PWC-131
Flame Cut Plates, A514 Steel.

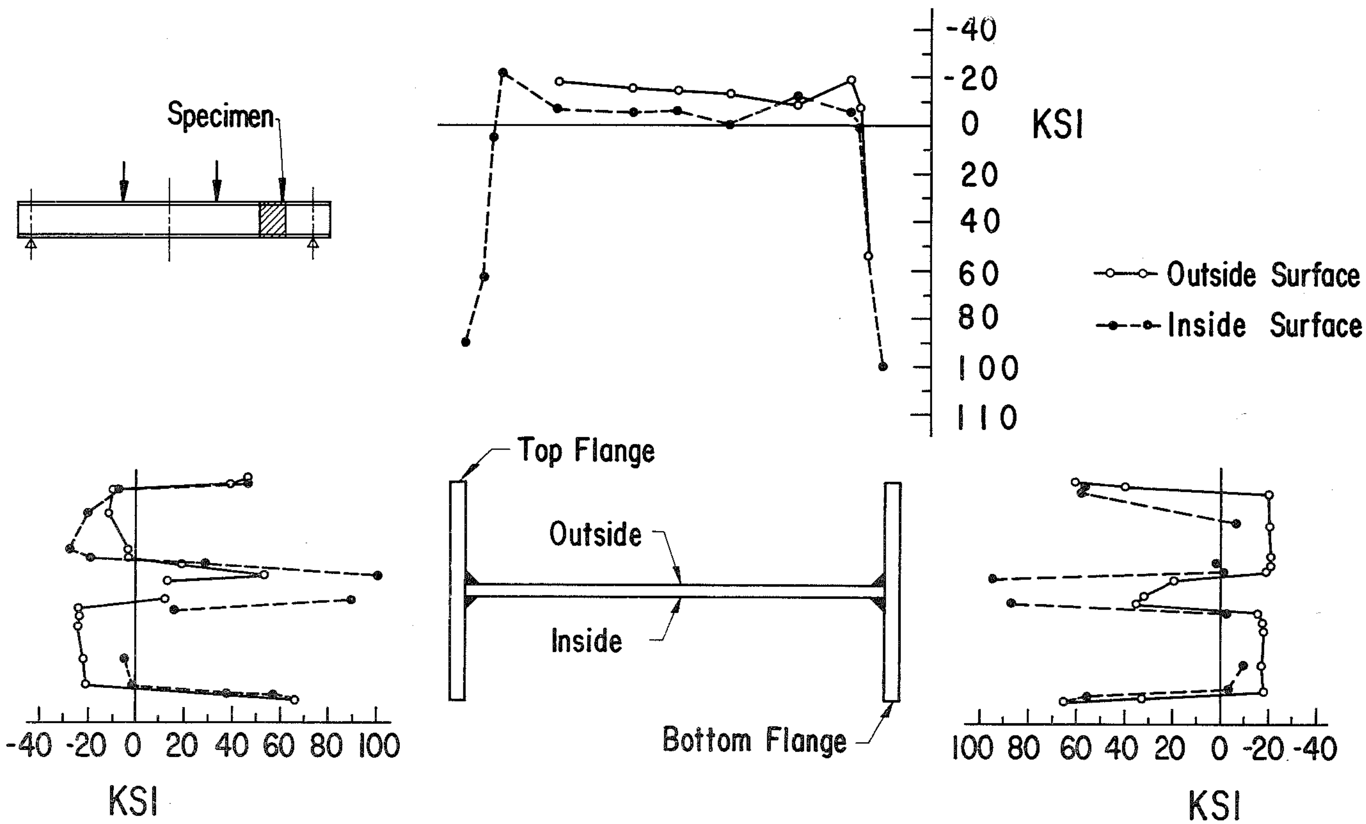

Fig. 5 Residual Stresses in a Welded Shape PWC-131
Flame Cut Plates, A514 Steel.

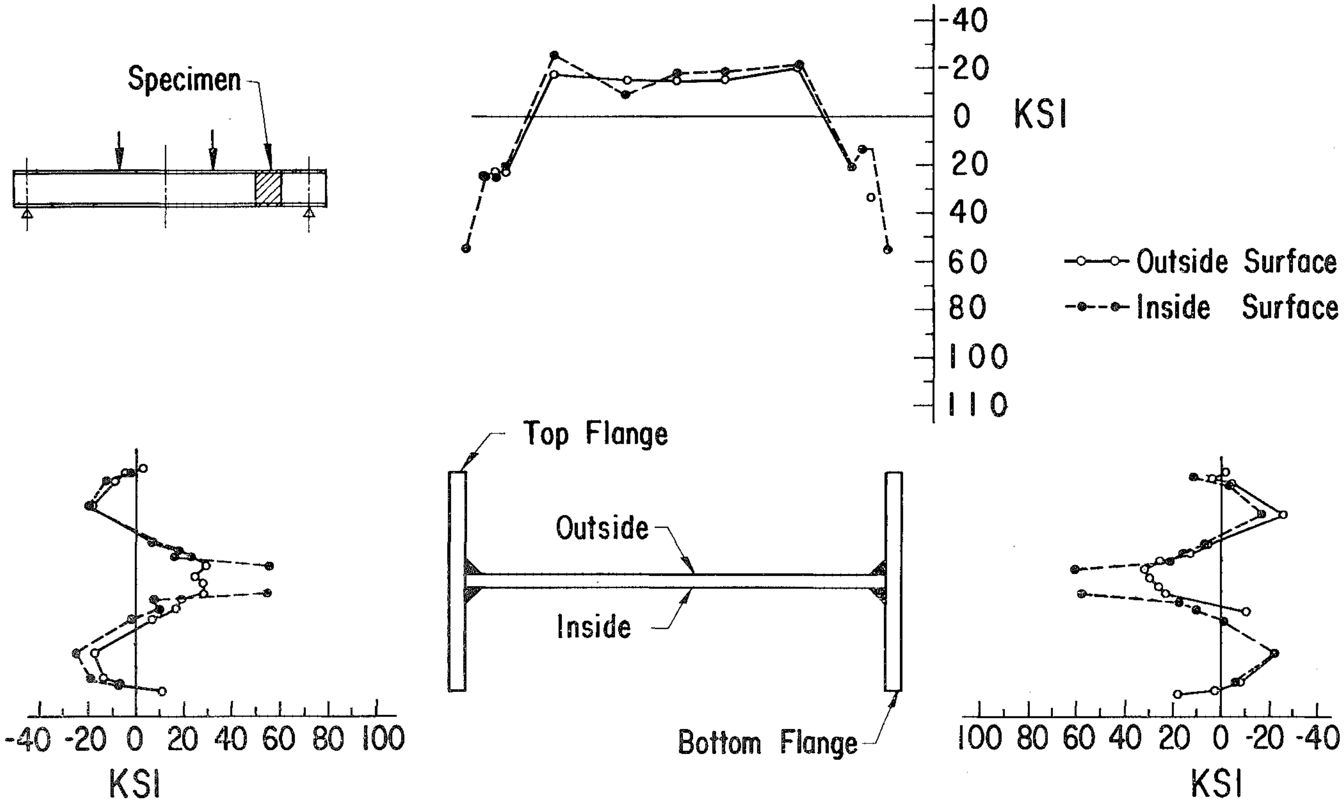

Fig. 6 Residual Stresses in a Welded Shape PWA-131
Flame Cut Plates, A36 Steel.

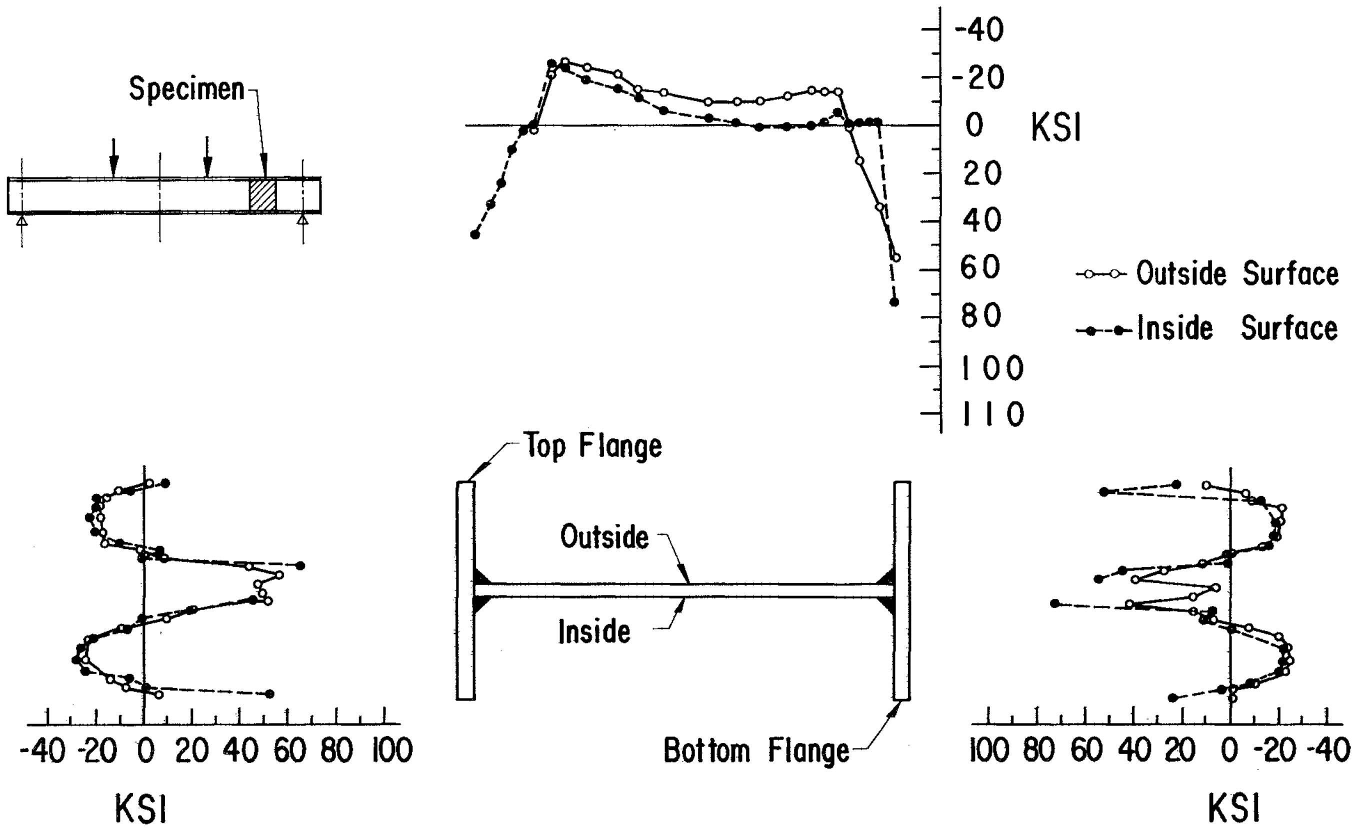

Fig. 7 Residual Stresses in a Welded Shape PWB-311
Flame Cut Plates, A441 Steel.

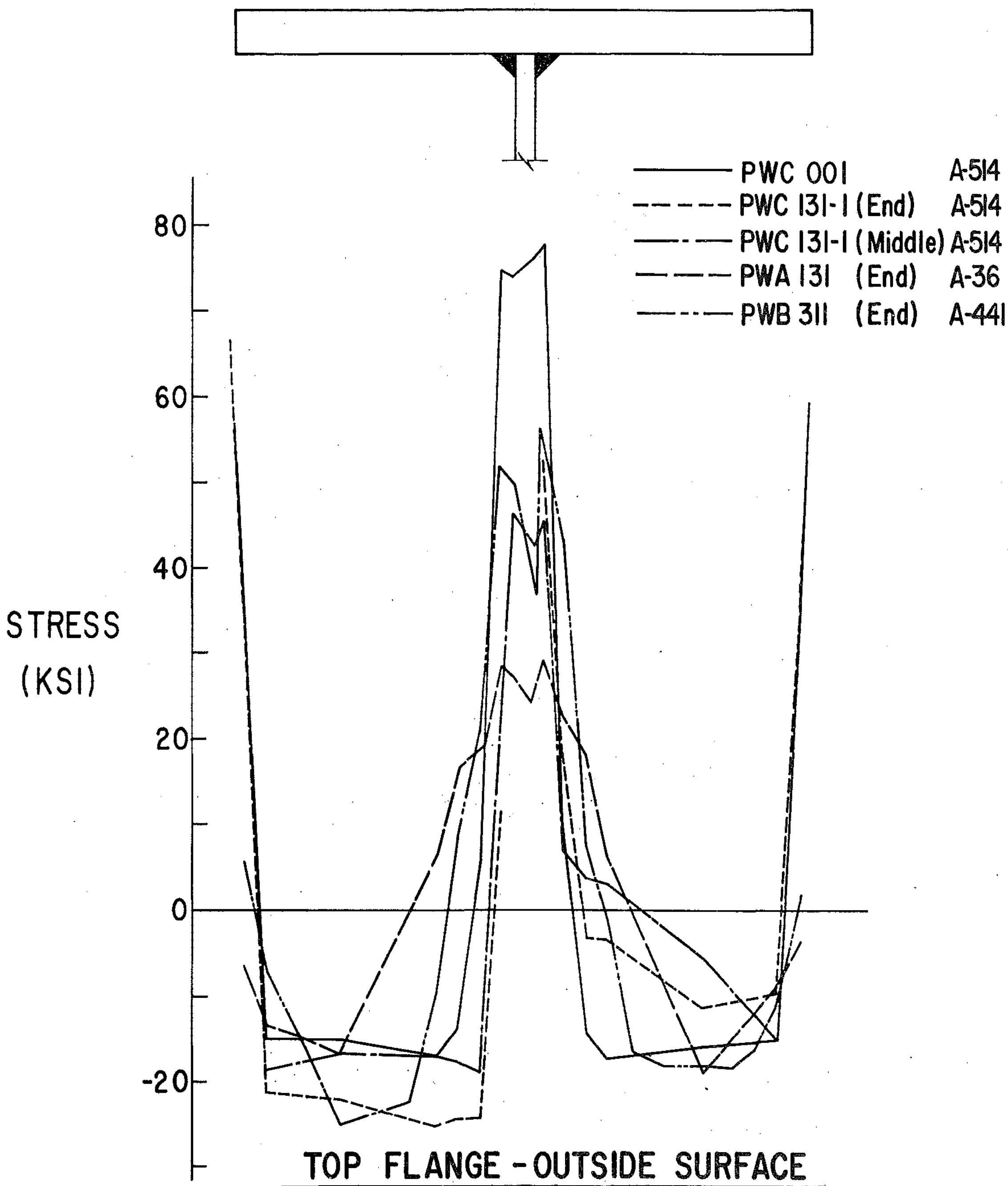

Fig. 8 Comparison of Residual Stress Distribution in the Top Flanges (Outside Surface).

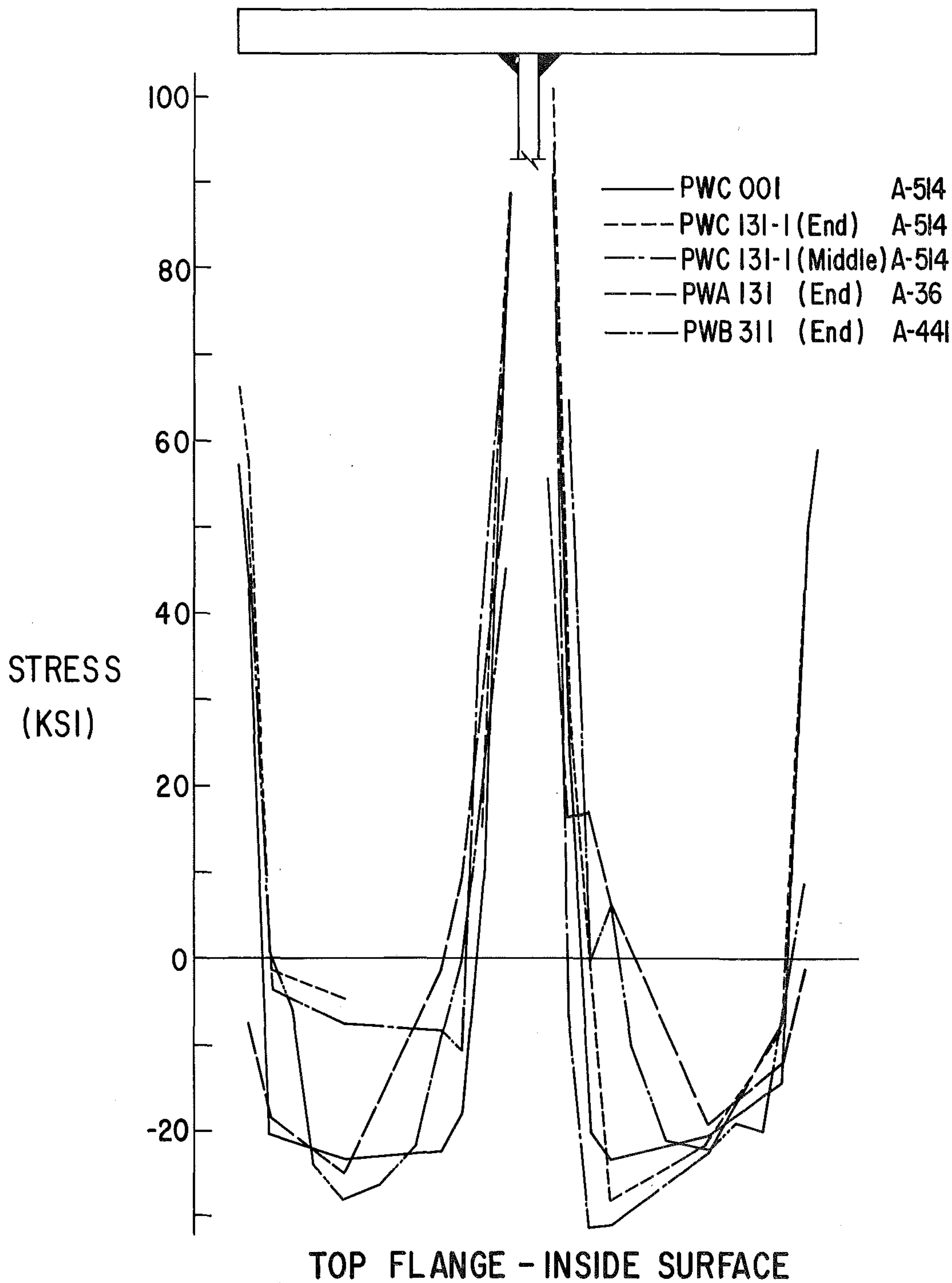

Fig. 9 Comparison of Residual Stress Distribution in the Top Flanges (Inside Surface).

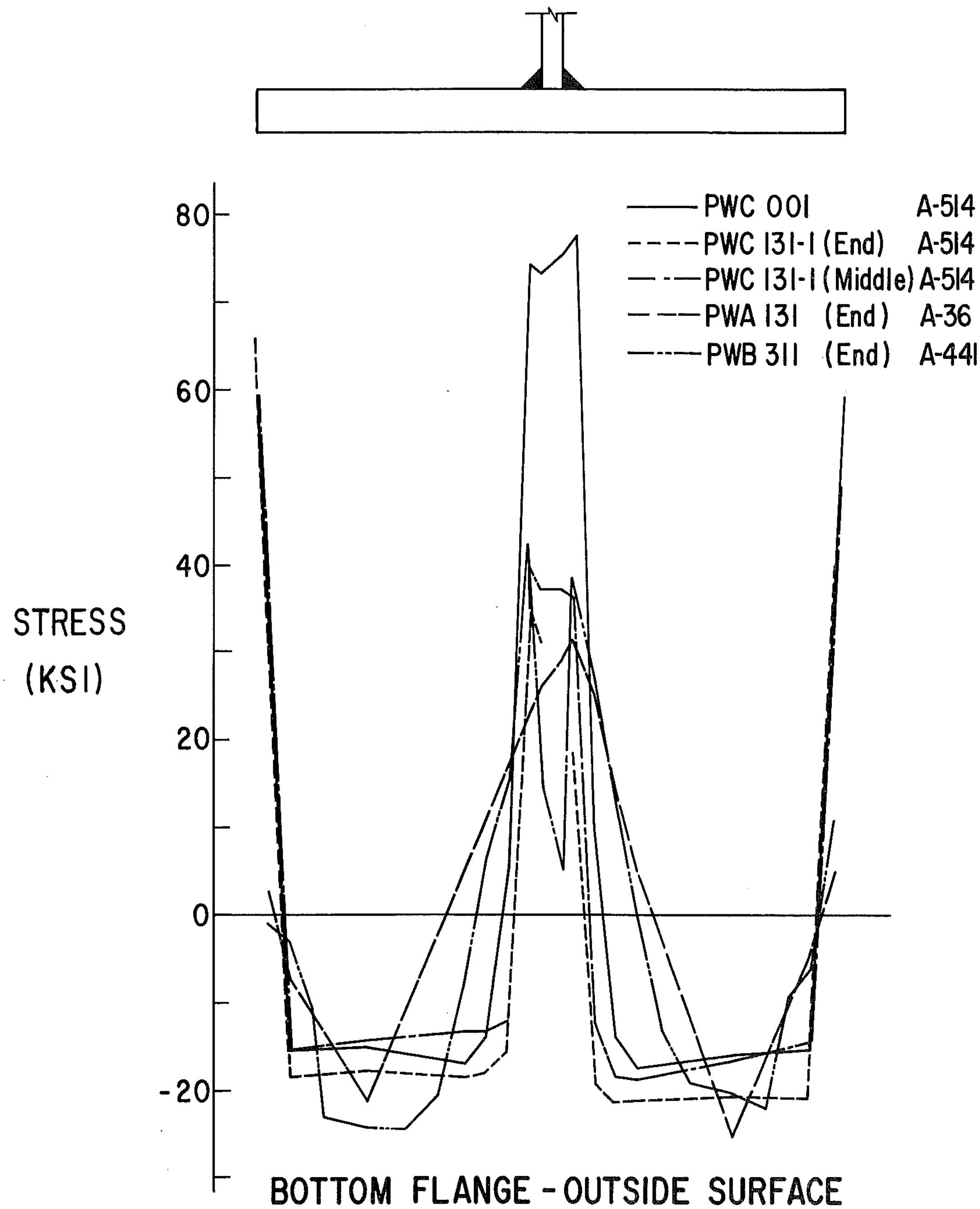

Fig. 10 Comparison of Residual Stress Distribution in the Bottom Flange (Outside Surface).

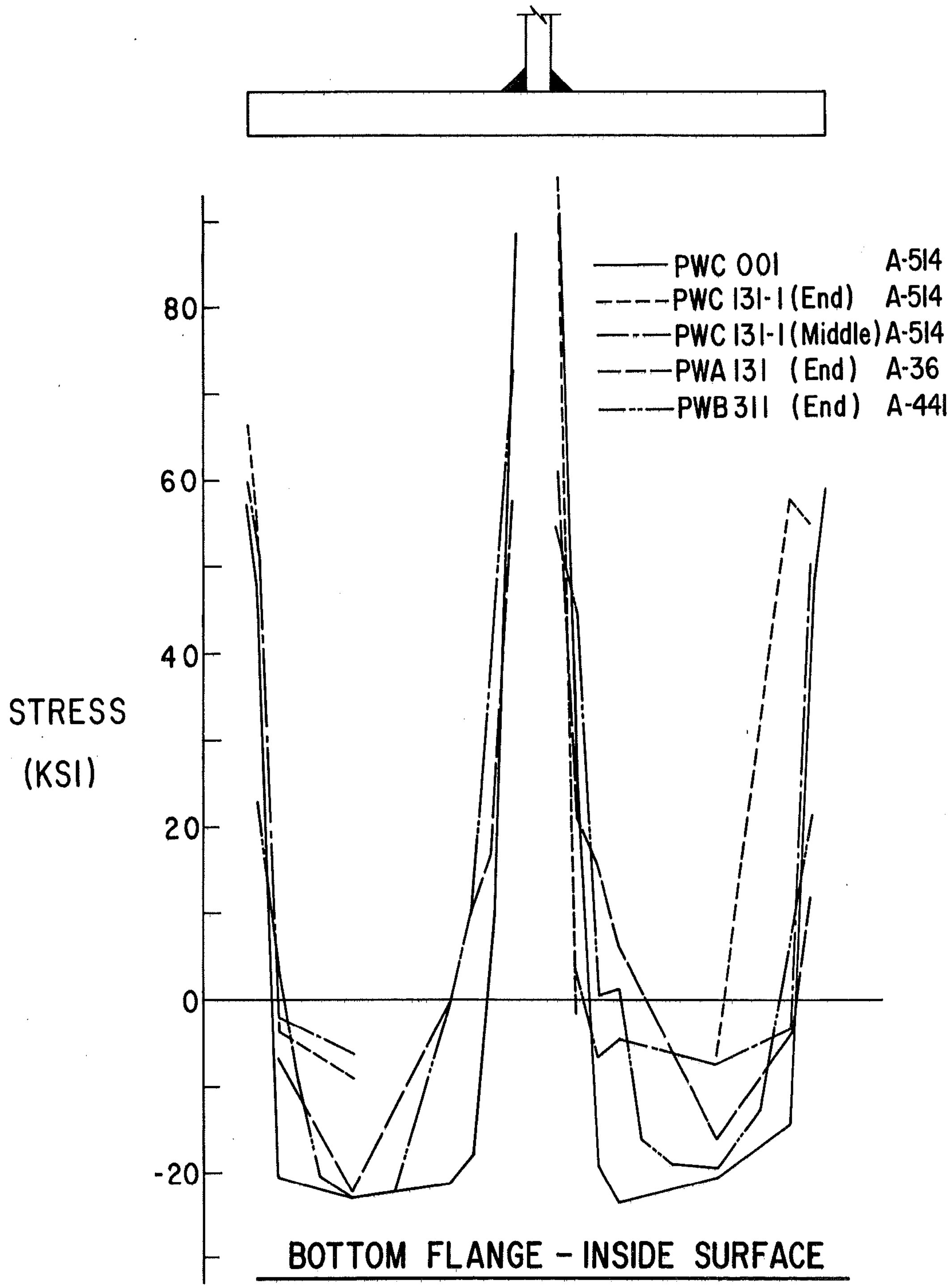

Fig. 11 Comparison of Residual Stress Distribution in the Bottom Flange (Inside Surface).

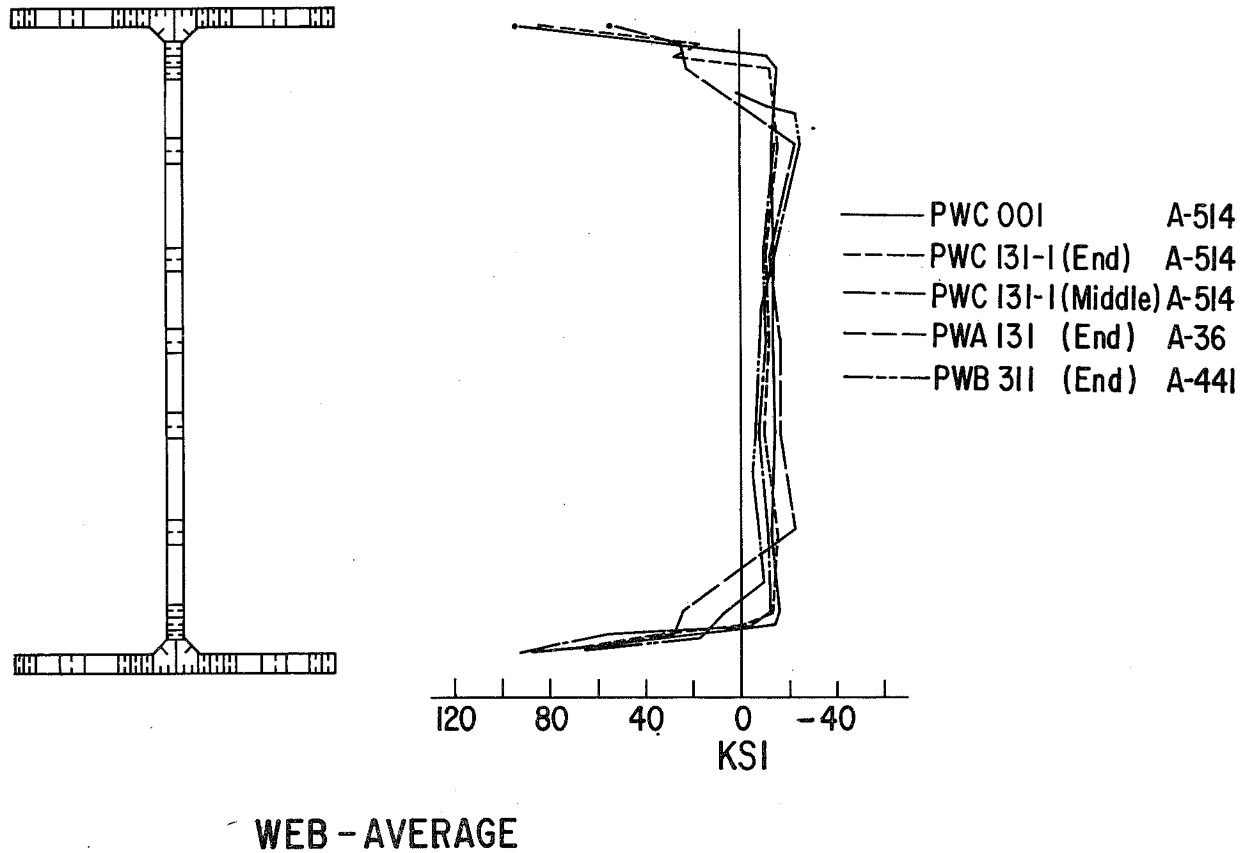

Fig. 12 Comparison of Residual Stress Distribution in the Webs.

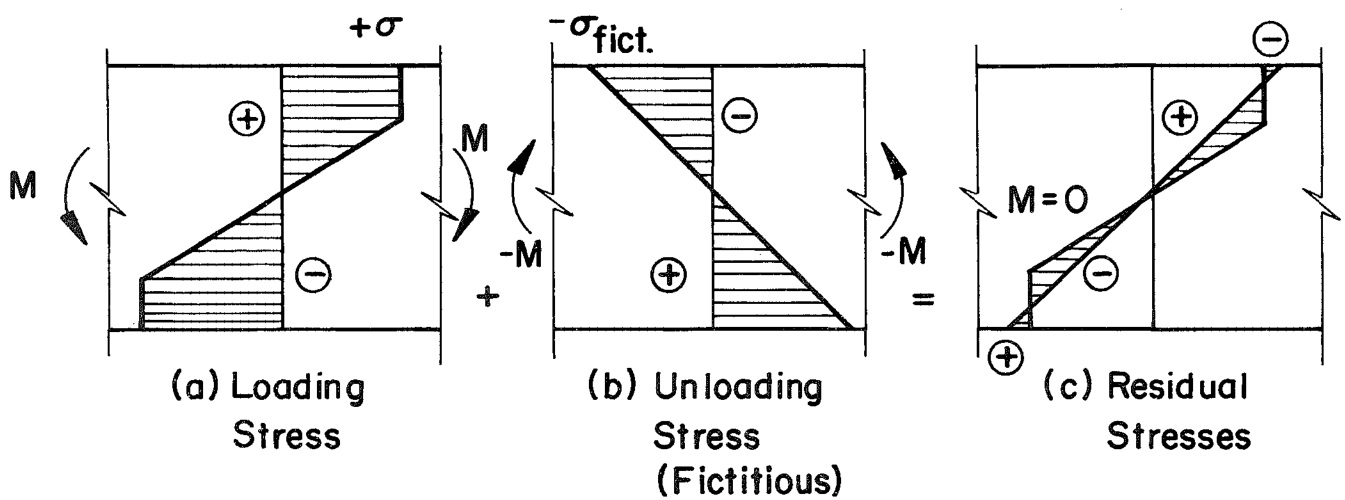

Fig. 13 Assumed Scheme for the Evaluation of Residual Stresses after Unloading.

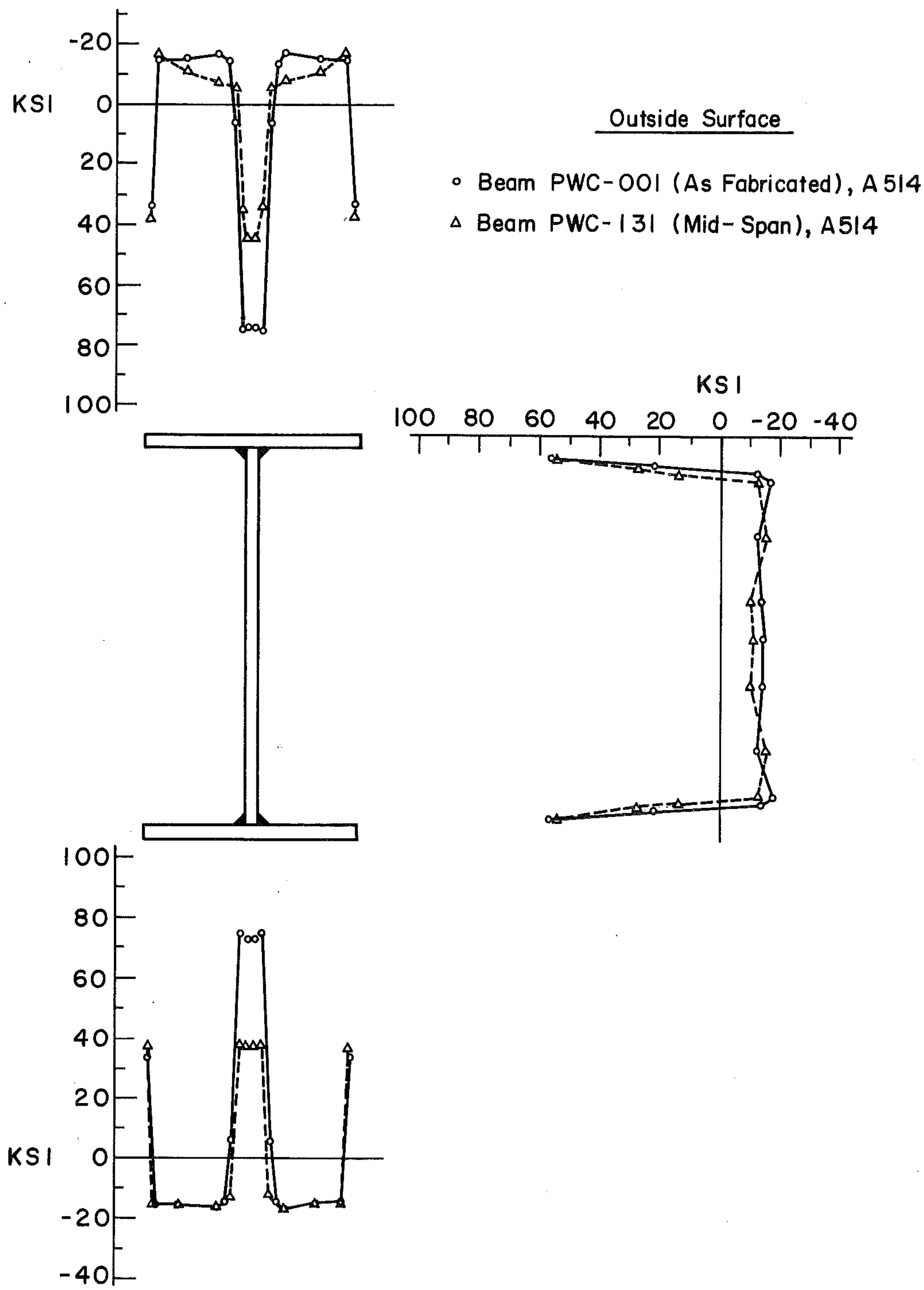

Fig. 14 Residual Stress Distribution in the Beam PWC-001 and the Beam PWC-131 (Mid-Span). Outside Surface.

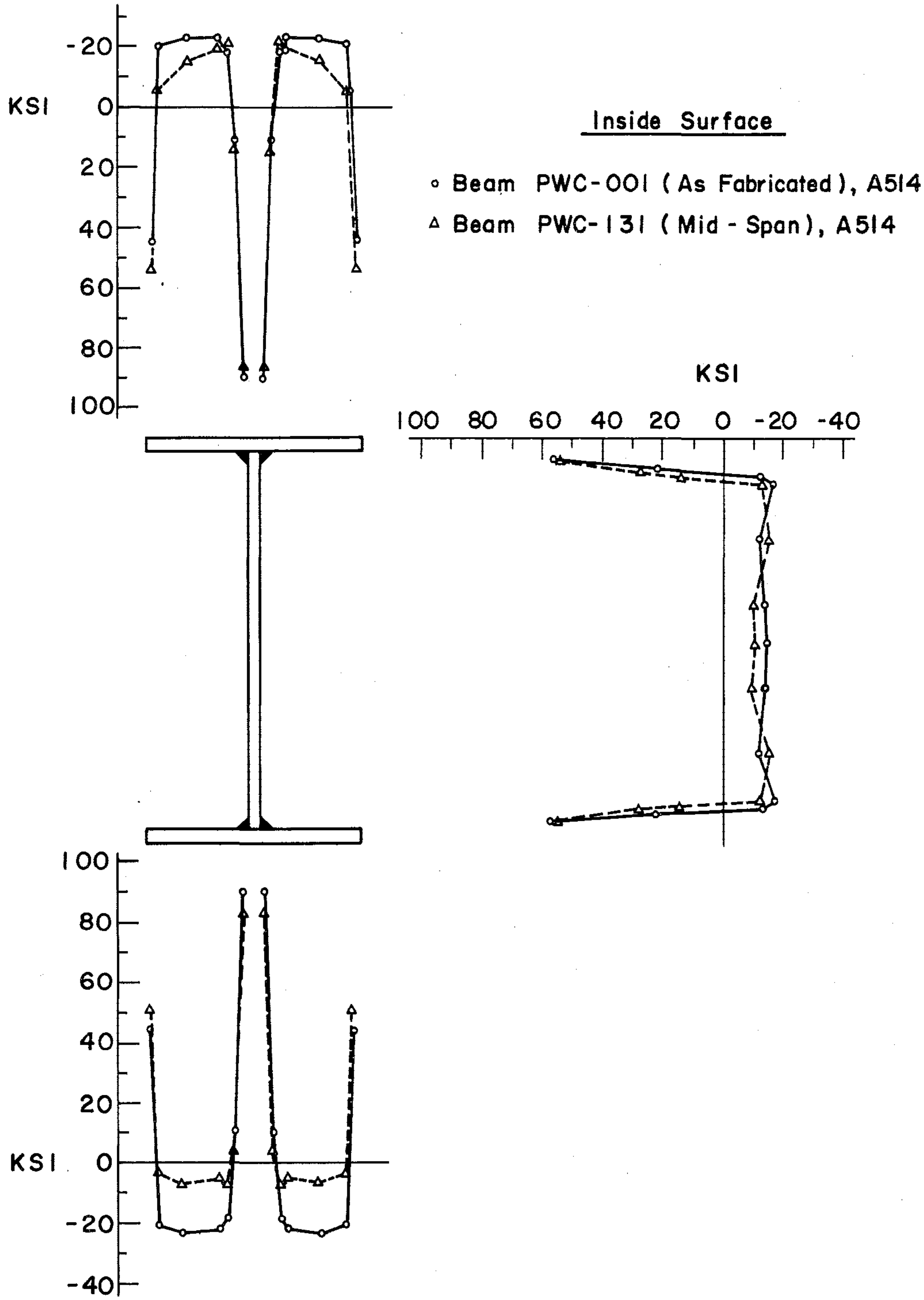

Fig. 15 Residual Stress Distribution in the Beam PWC-001 and the Beam PWC-131 (Mid-Span). Inside Surface.

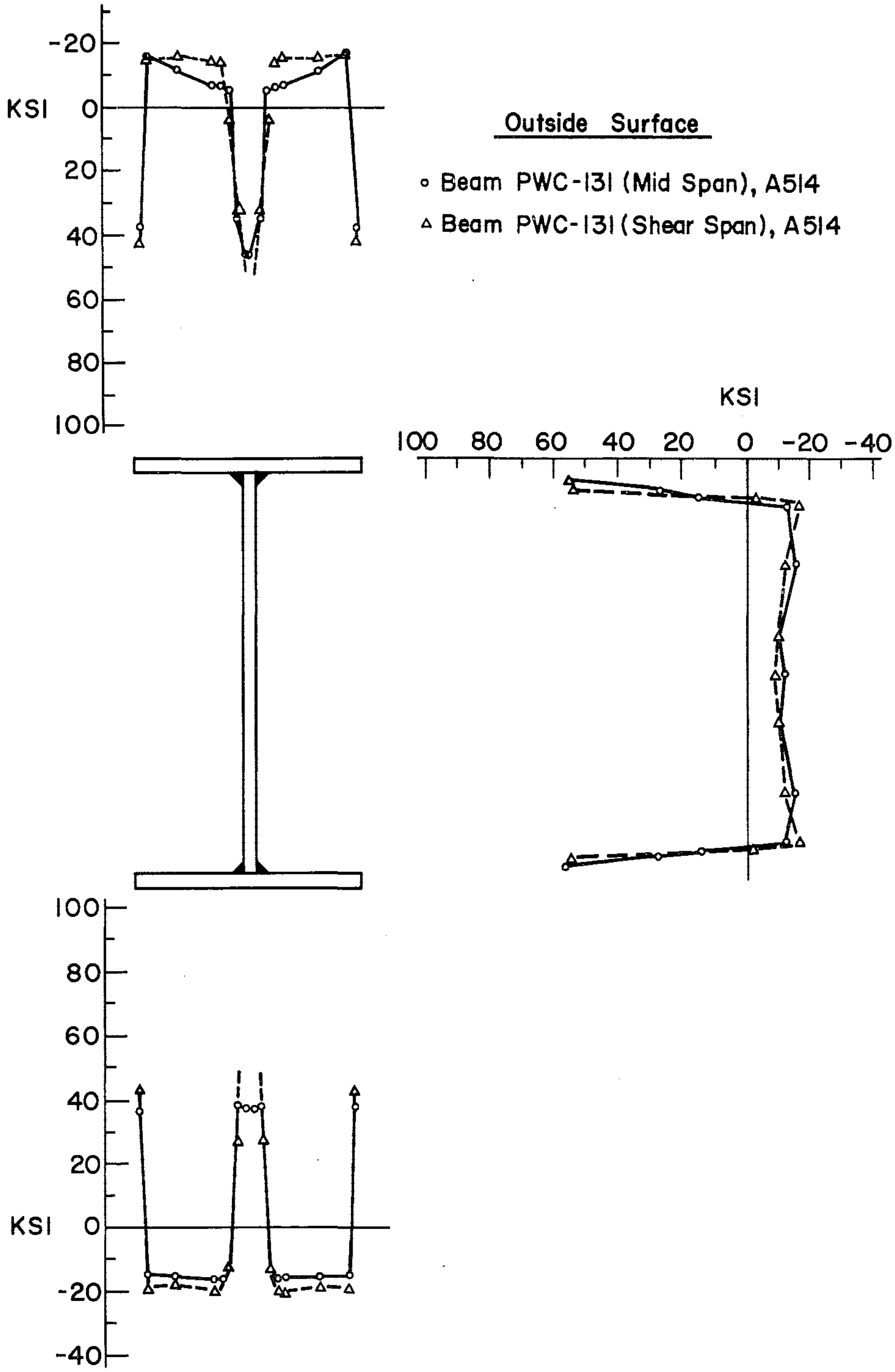

Fig. 16 Residual Stress Distribution in the Beam PWC-131 (Mid-Span) and the Beam PWC-131 (Shear-Span). Outside Surface.

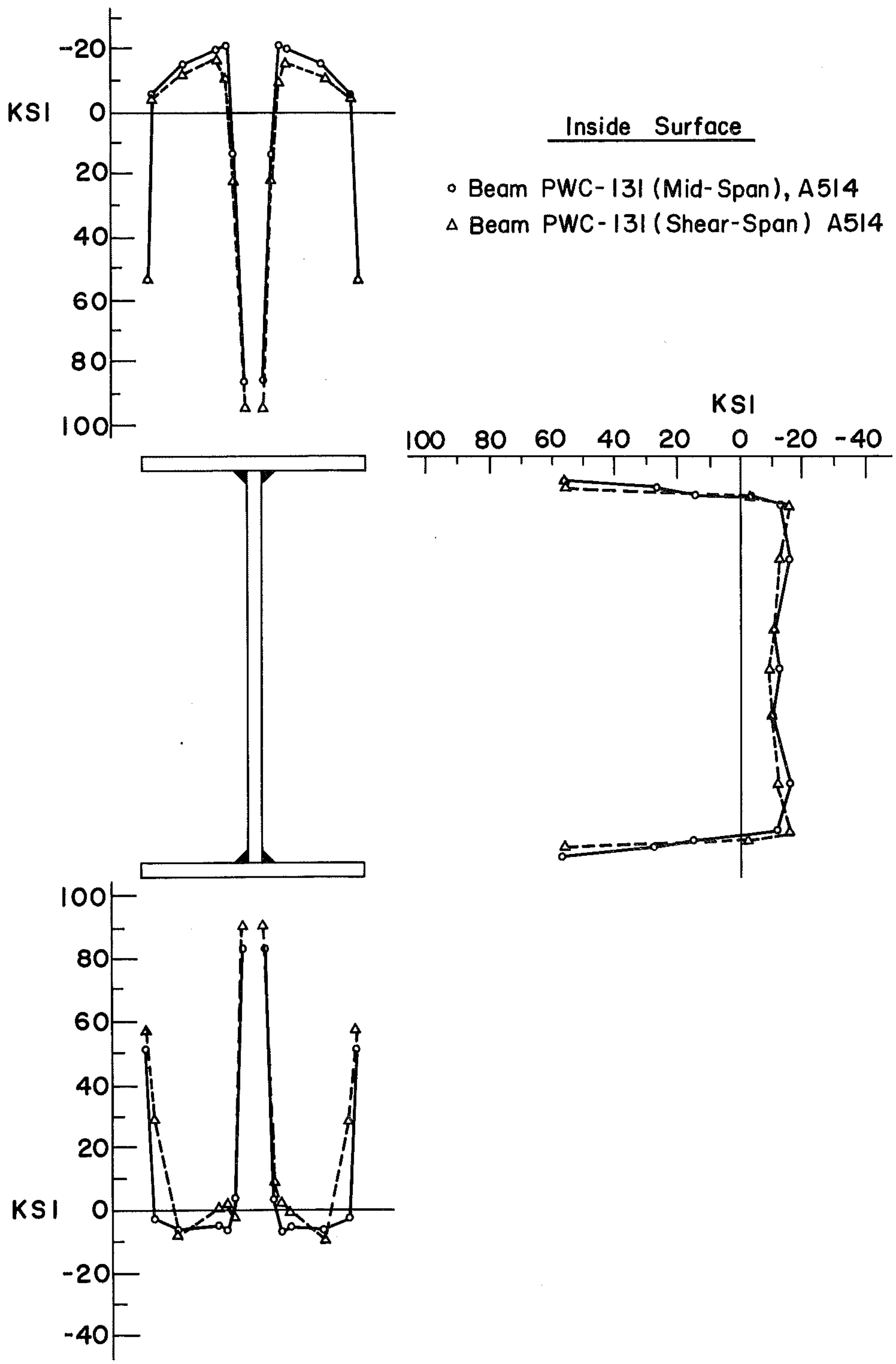

Fig. 17 Residual Stress Distribution in the Beam PWC-131 (Mid-Span) and the Beam PWC-131 (Shear-Span). Inside Surface.

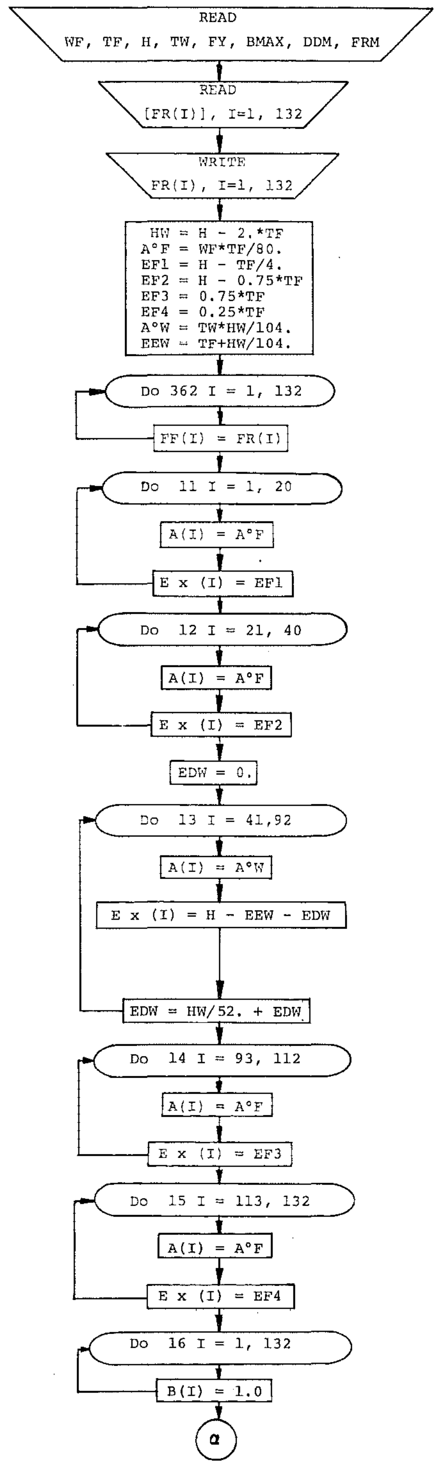

Fig. 18a Flow Chart (Part I)

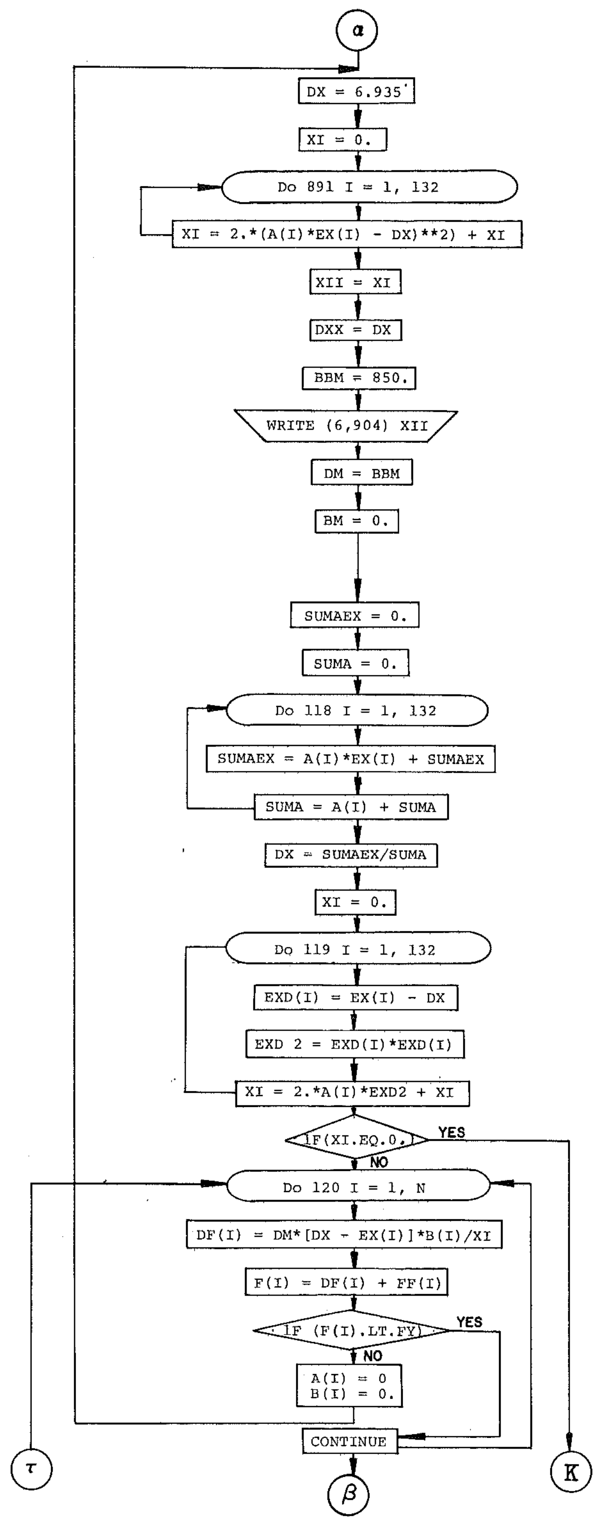

Fig. 18b Flow Chart (Part II)

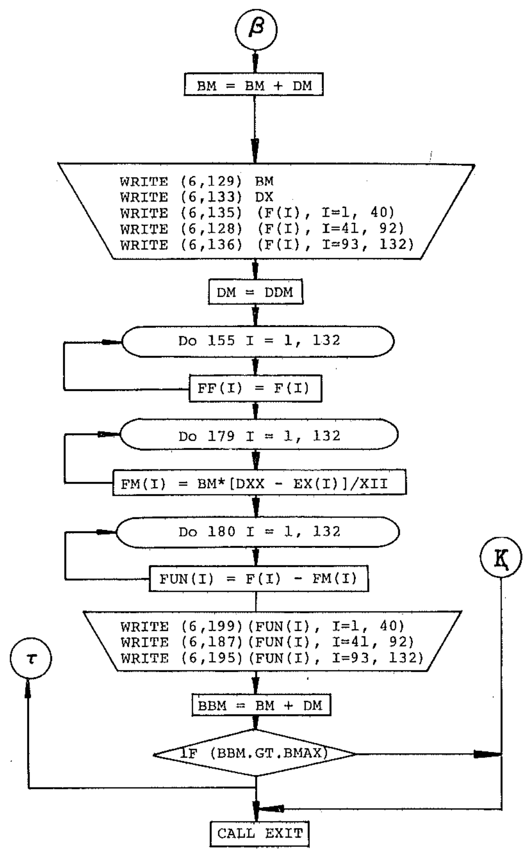

Fig. 18c Flow Chart (Part III)

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13. ABSTRACT

The purpose of this investigation is to compare the residual stresses in an as-fabricated beam with those in similar beams after a number of bending cycles.

The study is a part of a major research program designed to provide information on the behavior and design of joined structures to low cycle fatigue.

Four beams fabricated from flame-cut plates were evaluated, and three different steel grades ASTM A514, A441 and A36, were considered.

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